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DRAFT -- FOR DISCUSSION PURPOSES ONLY

1. (Currently Amended) A display communications device comprising:

a housing that contains a processor;

means, coupled to the processor, for receiving input radio signals; and

a ~~collapsible~~ flexible display that is mechanically coupled to the housing and electrically coupled to the processor, the flexible display including a flexible substrate, an active-matrix backplane arranged on the flexible substrate, and a plurality of organic light emitting devices (OLEDs) arranged on the active-matrix backplane,

wherein the display is ~~collapsible~~ rollable into the interior of the housing, wound at least one complete revolution upon itself, and has a viewable surface area that is larger than any cross-sectional area taken through the housing, and wherein the processor is adapted to extract display data from the input radio signals, and to provide a representation of the display data to the display.

44.3L: A Printed and Rollable Bistable Electronic Display

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The achievement of highly flexible reflective display media has been a persistent goal in the development of electronic displays [1-9]. The advantages of flexible electronic media over glass are clear: improved durability, lighter weight, thinner dimensions, and the ability to integrate the display into curved or flexible devices. Reflective media hold interest over emissive displays due to the potential for low power consumption, simplifying device design.

Despite this great interest, there are relatively few examples of displays on flexible substrates, and these have only found moderate success. Plastic film-based liquid crystal displays, including twisted nematic (TN), supertwisted nematic (STN), polymer dispersed (PDLC), and bistable cholesteric liquid crystals have been demonstrated. Nevertheless, problems remain. The optical properties of TN and STN displays are highly sensitive to cell gap, making manufacture difficult and leading to stress-induced variations in the appearance of these devices. Local stress can also cause changes in the scattering, absorbance, or reflectance of PDLC and cholesteric films. Plastic-based TN and STN devices can also be troubled by the infusion of vapor into the cell, which can cause bubbles to appear. As such, only moderate flexibility can be achieved in these devices, and with varying degrees of increased effort and cost.

Emissive electroluminescent films and organic light emitting diode films can be deposited on flexible substrates, but require continuous power consumption for operation. Additionally, the stability of these devices is often compromised by air and water, which tend to permeate into plastic-based devices.

Rotating bichromal balls represent a reflective display technology that is both bistable and can be fabricated into flexible sheet form [10]. These devices to date, however, remain at an early developmental stage.

In liquid crystal and emissive devices, there is also concern about damage to the conductive traces used to address the display elements. Typically, a vacuum-sputtered indium tin oxide (ITO) layer on a plastic substrate is used as a conductor on one or more sheets. If the local curvature of the substrate becomes too high, then the ITO tends to crack, damaging the display. Vacuum-sputtered ITO on plastic is also costly, which limits its attractiveness for large-area or disposable displays.

We report here the development of a microencapsulated electrophoretic display medium which demonstrates unprecedented flexibility in a reflective, electrically-addressable display. The display does not use vacuum-sputtered ITO as the transparent conductor. The display is reflective, bistable, and can be produced entirely by a series of printing steps. As such, we anticipate that this construction will prove attractive in a number of display applications in which flexibility, durability, and low cost are important.

Basis of the flexible display

In order to achieve a highly-flexible, reflective, and electrically-addressable display medium, two problems must be surmounted:

- The display medium itself should not be damaged by significant flexing of the display, nor should the optical appearance of the display be affected significantly by high local curvature.
- The conductive traces used to address individual picture elements cannot become damaged or broken by repeated flexing.

Our microencapsulated electrophoretic prototype display solves both problems.

The use of microencapsulated electrophoretic inks has been reported by us at SID '97 [11]. Briefly, in one form of the ink an electrophoretically-mobile composite particle of a TiO_2 pigment and an organic polymer is mixed into an organic fluid closely matched in specific gravity to the particle. In the example described here, the organic fluid contains a blue dye. This fluid is emulsified into an aqueous solution and microencapsulated using standard procedures; for example, either gelatin-gum arabic or urea-formaldehyde microcapsules can be used. These microcapsules are blended with an aqueous-based binder, which comprises the printable electronic ink suspension.

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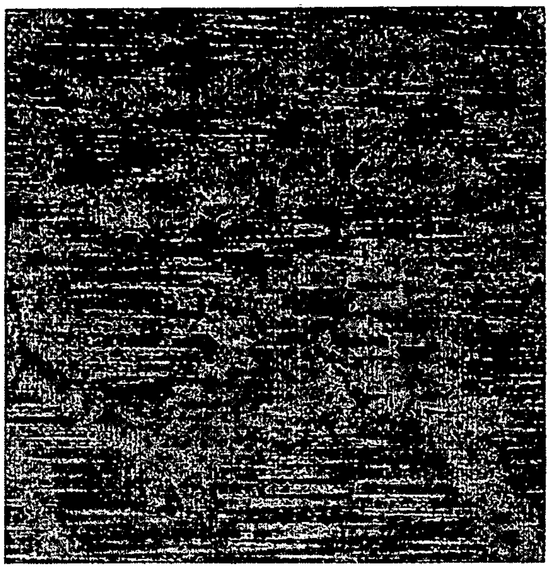

Figure 1: White state of electrophoretic displays. White particles are drawn to the viewing side of the display. The larger capsules are on the order of 100 microns in diameter.

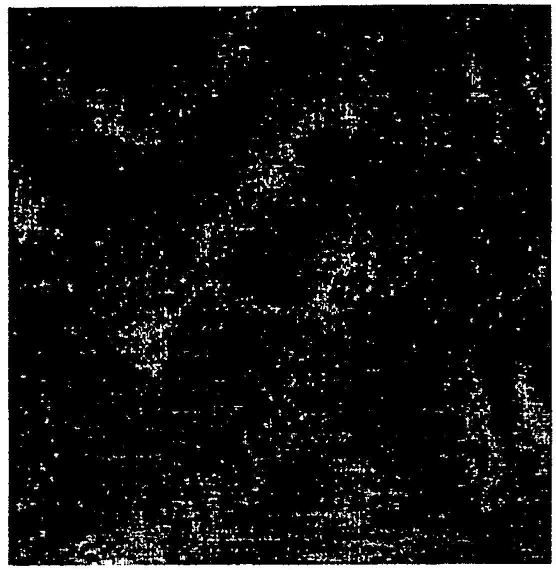

Figure 2: Dark (blue) state of electrophoretic display. White particles are drawn to the non-viewing side of the display.

The operation of the microencapsulated electrophoretic device is easy to visualize. When one polarity of voltage is applied to the device, the white particles are attracted to the front of the display, and that area appears white. When the opposite polarity is applied, the white particles move to the rear of the capsules. The viewer now sees the dyed fluid, and that area of the display appears colored. Intermediate gray levels can be achieved by partial movement of the particles from one surface to the other through control of the voltage pulse amplitude or duration. Once set, the particles do not move appreciably over time, and the optical appearance is stable. Figures 1 and 2 shows some microcapsules in each of the two optical states.

The microencapsulation of the electrophoretic fluid enables the application of this display technology to flexible substrates. The microencapsulation serves to compartmentalize the electrophoretic particles, preventing lateral drift and agglomeration into low-field areas of the display. This solves an important stability problem that was recognized during earlier efforts to commercialize electrophoretic displays [11-14]. The use of a flexible binder between microcapsules allows for significant flexure of the substrate without affecting the optical appearance of the display; the electrophoretic particles remain in the same position within the microcapsule irrespective of the position or curvature of the binder and film.

Basis for low-cost display conductors

The electrophoretic effect enables another valuable feature of this display: the ability to use relatively inexpensive conductors in the display stack. In particular, we can avoid the use of vacuum-sputtered ITO, a material with costs on the order of several dollars per square foot.

In the display described here, the rear, patterned conductor can be either opaque or transparent. This allows for the use of a variety of printed conductors, including graphite inks, silver inks, or conductive polymers.

The front conductor must be transparent, but does not need to be tremendously conductive. The electrophoretic display material is of remarkably high resistivity. The current passed by the movement of the electrophoretic particles is extremely small. An idea of the order of magnitude of the conductance needed to address the display can be obtained by considering the *RC* time constant of the system. The capacitance C of a pixel of thickness d and area A is given by the familiar equation

$$C = A\,\varepsilon\,\varepsilon_0 / d.$$

Here, ε and ε_0 are the dielectric constant of the cell materials and the free space permittivity, respectively. When the display driven by a square wave and is not updated very rapidly (*i.e.* low frequencies), we can assume that a pixel charging time given by the value of

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$4{*}RC \leq 0.1$ s is sufficient to drive the display. A quick calculation shows that for an electrophoretic cell with $A = 10\ \text{cm}^2$, $d = 50$ microns, and $\varepsilon = 2$, the capacitance is of the order of 250 pF. This leads to the requirement of $R \geq 400\ \text{M}\Omega$. While practical considerations would likely favor a lower resistivity for the conductive backplane and leads than this value, this calculation demonstrates that relatively poor conductors (with resistivities greater than 10^6 ohm/square) can be used either as lead lines or common planes in the display stack. This conductivity range is in the range of a number of conductive colloidal suspensions and conductive polymers that are commonly used in anti-static applications.

The replacement of vacuum-sputtered ITO is beneficial in a several ways. The printable conductor we use here can be coated thinly, providing both low reflection and coloration from the conductor. Additionally, these coatable conductors are significantly less expensive than vacuum-sputtered ITO, leading to the removal of a major cost item in an electronic display.

Another benefit is that the electrode never comes into contact with the electrophoretic fluid, but is coated onto a solid binder. This construction feature allows for the use of conductive polymer systems that might be swollen or degraded when put into contact with a good solvent (like a liquid crystal). This opens the door for use of a wide number of intrinsically-conductive polymer systems, including derivatives of polyaniline, polypyrrole, polythiophene, and polyphenylenevinylene.

Design of the flexible display

To construct a display, a 4 mil thick sheet of polyester is printed with a transparent conductive coating, described below. On top of this conductor is printed the electrophoretic suspension, followed by a patterned graphite or silver layer. The individual elements in this rear conductor can be addressed using lead lines on this layer, or through the use of vias printed using a combination of printed dielectric and conductive materials. This all-printed stack is shown schematically in Figure 3.

The optical appearance of the microencapsulated medium itself is more-or-less unaffected by curvature larger than the approximate size of the microcapsules themselves. In this prototype, the average cell gap is on the order of 100 microns, which allows for significant bending of the display substrate without permanent deformation of the capsules themselves.

Figures 4 and 5 show a bistable microencapsulated display prototype in flat and not-so-flat states, respectively.

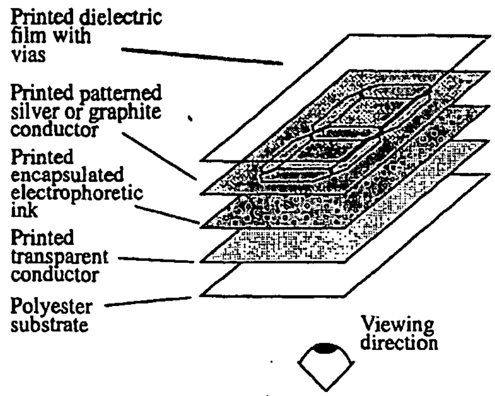

Figure 3. Schematic of layers in flexible electrophoretic display. Each layer is sequentially printed on top of the polyester film base. For clarity, the via holes and lead lines in the top layer, used to address the patterned conductive ink, are not shown.

The microencapsulated electrophoretic display maintains the other features of electrophoretic displays, including high luminance, bistability, and low power consumption. This particular prototype (colored white on blue) shows a contrast ratio of 6:1 and 12% relative luminance at 540 nm (16% photopic luminance) with 90 V operation. We expect that future development will lead to significant voltage reduction and reflectivity improvement in the electro-optical properties of these devices.

Presently, our display prototypes are directly driven with one lead line per pixel. To achieve higher resolutions, an active matrix backplane is required. We are currently developing display materials with voltage requirements compatible with active matrix backplanes.

Expected applications

All components used in this display prototype construction are relatively inexpensive and printable. Cheap, printable, and flexible displays be used in applications in which paper is currently the display medium of choice. Some novel applications are:

- Disposable displays which can be tightly rolled or even folded.
- Displays placed onto or incorporated into highly flexible plastic substrates, fabric, or paper.
- Large-area displays which are highly portable (being rolled up for transportation) and affordable.

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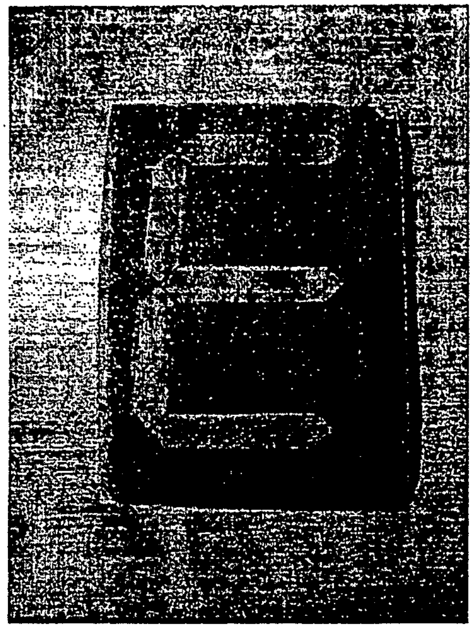

Figure 4. Encapsulated electrophoretic display in unrolled state.

This figure is reproduced in color on page 1269.

Figure 5. Encapsulated electrophoretic display in rolled state.

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